Designing your own pads, part 1

By Harold Kinley, CET

Attenuators and impedance-matching pads can be useful around the radio shop.

Attenuators and pads are used for RF and audio applications. Eventually, you may need to build your own attenuator for a special purpose. Here are a few basics about attenuators and pads that will help you when you build your own.

Pads are used for two basic purposes, impedance-matching and attenuation.

Unfortunately, with resistive components, you cannot design an impedance-matching network without significant attenuation. As undesirable as the loss may be, it is unavoidable with resistive networks.

Nevertheless, the attenuation often can be tolerated and *must* be taken into account when deciding whether or not a resistive pad is the best way to match impedance for a particular purpose.

L-pads

The simplest impedance-matching pad is the L-pad shown in Figure 1 below.

Upon close examination, you will notice that this L-pad is nothing more than a simple voltage-divider network. It consists of two resistors: one *arm* resistor, R_A, and one *leg* resistor, R_L.

This pad matches a 75Ω impedance with a 50Ω impedance.

If you must design an impedance-matching resistive network with *minimum loss*, an L-pad is the proper choice. Only one set of values for R_A and R_L satisfy an impedance match in both directions.

The L-pad is said to be *asymmetrical*. This means that the impedance does not look the same from both directions. Assuming that a 75Ω source is connected to Z_1 and a 50Ω load is connected to Z_2, the source sees an impedance of 75Ω.

Vice versa, when a 50Ω source is connected to Z_2 and a 75Ω load to Z_1 the source sees an impedance of 50Ω. Thus, the impedance match is bidirectional.

When designing an L-pad, first run the formula in Figure 1 for minimum loss. If this amount of loss is intolerable for the application, the L-pad is unsuitable.

Next, consider a matching network using reactive components (inductors and capacitors).

These sometimes are called *lossless* matching networks, though, in practice, a certain amount of insertion loss is inevitable. The disadvantage of reactive component matching networks is that they are frequency-sensitive and more difficult to build.

If an L-pad's minimum loss is acceptable, then you can determine the arm and leg resistance values R_A and R_L from the Figure 1 formulas. In building an L-pad such as the one in Figure 1 (75Ω/50Ω), be sure to mark the two ports with the proper impedance label.

Better yet, use an F connector for the 75Ω port and a BNC or other 50Ω connector for the 50Ω port. This will help to prevent reverse-connecting the L-pad.

Figure 1's L-pad attenuation is approximately 5.7dB.

Important points to remember about the L-pad are:

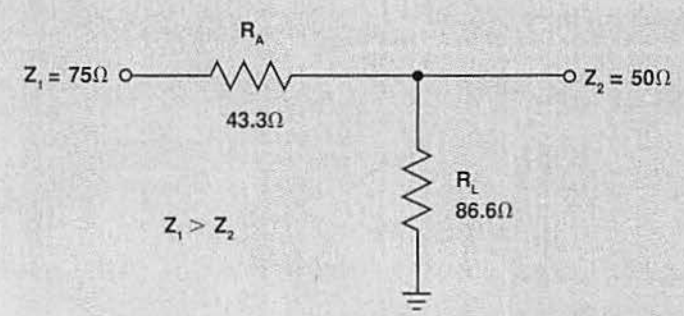
(1) It is asymmetrical—the impedance is different at each port.

(2) It is used to provide an impedance match between two unequal impedances.

(3) It cannot be used between two equal impedances if an impedance match is to be maintained in both directions.

(4) It cannot be used as an attenuator to provide more or less than the loss provided by the Figure 1 formula and still provide an impedance match in both directions.

(5) It is unbalanced.



(1) Minimum loss (dB) $= 20 \log \left(\sqrt{\frac{Z_1}{Z_2}} + \sqrt{\frac{Z_1}{Z_2} - 1} \right)$

(2) $R_A = \sqrt{Z_1(Z_1 - Z_2)}$

(3) $R_L = \frac{Z_1 Z_2}{R_A}$

Figure 1. The simplest impedance-matching pad is the L-pad, which is nothing more than a simple voltage-divider network. It consists of two resistors: one *arm* resistor, R_A, and one *leg* resistor, R_L.

T-pad

Some of the L-pad's shortcomings can be overcome with a T-pad.

Figure 2A on page 49 shows a T-pad. It can be used between equal impedances to provide any degree of attenuation and still maintain an impedance match in both directions.

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A T-pad also can be used to provide a bidirectional impedance match between two unequal impedances *and* provide an attenuation *equal to or greater than* the loss provided by Figure 1's minimum-loss formula.

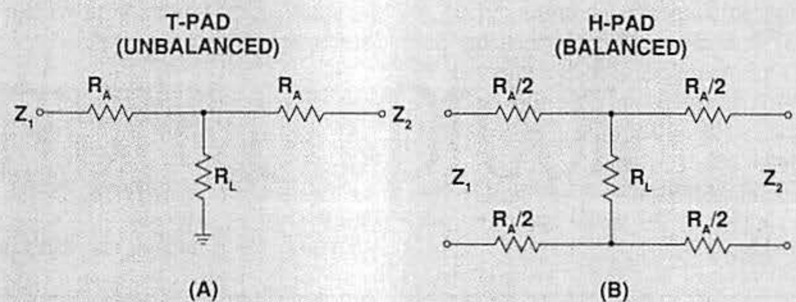
The minimum-loss formula applies to T-pads *only when the input and output impedances are not equal.*

Notice that the T-pad has two arm resistances (R_A) and a single leg resistance (R_L). The Figure 2 formulas can be used to calculate R_A and R_L only when the input/output impedances are equal.

The T-pad is unbalanced. It is symmetrical when the input/output impedances are equal. With unequal input/output impedances, it is asymmetrical.

Important points to remember about a T-pad are:

(1) It is unbalanced.



If $Z_1 = Z_2$ then:

(4) $R_A = Z\left(\frac{K-1}{K+1}\right)$

(5) $R_L = Z\left(\frac{2K}{K^2-1}\right)$

(6) ______________ where: $K = 10^{(dB/20)}$ = antilog (dB/20)
(dB = desired attenuation)
Z = system impedance

Figure 2. The T-pad (A) can be used between equal impedances to provide any degree of attenuation and still maintain an impedance match in both directions. It can be used to provide a bidirectional impedance match between two unequal impedances *and* provide an attenuation *equal to or greater than* the loss provided by Figure 1's minimum-loss formula. The H-pad (B) exhibits all of the T-pad's characteristics, except it is *balanced.*

(2) It is symmetrical when the input/output impedances are equal.

(3) It is asymmetrical when the input/output impedances are unequal.

(4) The minimum-loss formula applies with unequal input/output impedances.

(5) The minimum-loss formula does not apply with equal input/output impedances.

(6) It can provide a greater loss than the simple L-pad and still provide a bidirectional impedance match.

6dB T-pad calculation

To design a T-pad for 6dB attenuation, use the Figure 2 formulas.

First, find the K factor to use in the formula for R_A and R_L.

To find the K factor, use formula 6 in Figure 2. For 6dB attenuation, the K factor is:

$$K = \text{antilog}(6/20) = \text{antilog}(0.3) = 1.995\text{, rounded to } 2.0$$

Substituting for K in formula 4:

$$R_A = 50[(2 - 1)/(2 + 1)] = 50(1/3) = 50/3 = 16.7\Omega$$

Substituting for K in formula 5:

$$R_L = 50[(2 \times 2)/2^2 - 1)] = 50(4/3) = 200/3 = 66.7\Omega$$

H-pad

The H-pad exhibits all of the T-pad's characteristics, except it is *balanced*.

It consists of four arm resistances (R_A) and one leg resistance (R_L). (See Figure 2B.) The arm resistances each are one-half of the equivalent T-pad value.

A 6dB H-pad can be made using the above calculations. Simply divide the arm resistances calculated for the T-pad (16.7Ω) by 2 to get the H-pad arm resistance. Thus, the H-pad equivalent is four arm resistances of 16.7/2 or 8.4Ω each.

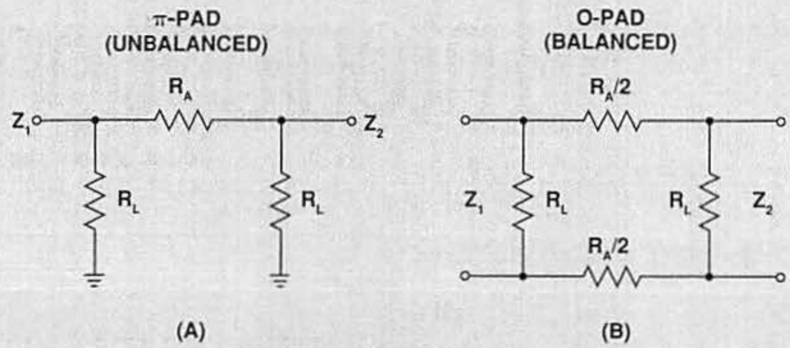
The leg resistance remains the same, 66.7Ω.

π-pad

The π-pad exhibits the same characteristics as the T-pad.

It is called a π-pad because it is shaped like the Greek letter π. (See Figure 3A on page 52.) The Figure 3 for-

Technically speaking



If $Z_1 = Z_2$ then:

(7) $R_A = Z\left(\frac{K^2-1}{2K}\right)$

(8) $R_L = Z\left(\frac{K+1}{K-1}\right)$

(6) ______________ where: $K = 10^{(dB/20)}$ = antilog (dB/20)

(dB = desired attenuation)

Z = system impedance

Figure 3. The π-pad (A) exhibits the same characteristics as the T-pad (Figure 2A). It is called a π-pad because it is shaped like the Greek letter π. The Figure 3 formulas apply only when the input/output impedances are equal. The O-pad (B) is the *balanced* counterpart of the π-pad. All other characteristics are the same as the π-pad. The arm resistances each are one-half of the equivalent π-pad value.

mulas apply only when the input/output impedances are equal.

6dB π-pad calculation

To design a 6dB π-pad, first find the K factor. (See formula 6 in Figure 3). The K factor is the same as it was for the 6dB T-pad design previously shown: 2.0.

Substituting into formula 7:

R_A

$= 50[(2^2 - 1)/(2 \times 2)]$

$= 50(3/4)$

$= 150/4$

$= 37.5\Omega$

and

R_L

$= 50[(2 + 1)/(2 - 1)]$

$= 50(3/1)$

$= 150/1$

$= 150\Omega$

O-pad

The O-pad is the *balanced* counterpart of the π-pad. (See Figure 3B.)

All other characteristics are the same as the π-pad. The arm resistances each are one-half of the equivalent π-pad value.

To design a balanced 6dB O-pad, simply divide the 6dB π-pad arm resistance by 2. This is $37.5/2 = 18.75\Omega$ for each arm resistance shown in Figure 3B.

Next month you will see how π-to-T and T-to-π transformations are used to design and simplify impedance-matching pads.

Construction and testing of resistive attenuator and matching pads also will be covered.

Designing your own pads, part 2

By Harold Kinley, CET

Attenuators and impedance-matching pads can be useful around the radio shop.

Attenuators and pads are used for RF and audio applications. Eventually, you may need to build your own attenuator for a special purpose.

In February's column, a few basics about L-pads, T-pads and π-pads were discussed that will help you when you build your own.

The conversion of T-pads to π-pads and π-pads to T-pads can help you reduce a *combination* of L-pad and π-pad or T-pad to one simple equivalent π-pad or T-pad for impedance matching.

Conversions

Here is how to convert π-pads to T-pads and vice versa.

Figure 1A shows a T-pad with resistance labeled R_1, R_2 and R_3. An equivalent π-pad is shown at 1B.

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The π-pad resistances are labeled R_a, R_b and R_c. The figure's formulas can be used to convert from a T-pad to an equivalent π-pad and vice versa.

Using an electronic calculator with a memory function, it is easy to apply the formulas. Notice that in converting from T-pads to π-pads, the numerators are the same for each resistance calculation. The numerator can be stored in the calculator's memory and reused for each resistance calculation.

In the π-pad to T-pad conversions, the denominators are the same for each resistance calculation. For these conversions, the denominator can be stored in memory for reuse.

Practical application

Figure 2A is a simple L-pad.

The L-pad is used to match a 75Ω impedance to a 50Ω impedance. This pad attenuates the signal by approximately 5.7dB. Because this is an odd value, it might be desirable to change the attenuation to an even value, such as 10dB.

It would be impossible to build an L-pad to provide a *bidirectional* 75Ω/50Ω impedance match at a 10dB loss. Nevertheless, by using a π-pad with an attenuation of 4.3dB in cascade with the L-pad, an equivalent T-pad with 10dB attenuation can be derived.

A π-pad with 4.3dB attenuation is shown in Figure 2B. The L-pad and π-pad are connected in cascade. (See Figure 2C.) Notice that R_L of the L-pad and R_a of the π-pad are connected directly in parallel.

These two resistances can be replaced with a single 60Ω resistance, R_a, shown at Figure 2D. Upon further examination of Figure 2D, you will notice that a new π-pad has emerged. It consists of resistances R_a, R_b and R_c.

Using the conversion information from Figure 2, the π-pad at Figure 2D can be transformed into a T-pad, as shown at Figure 2E.

Upon further examination of the resulting pad at Figure 2E, you will notice that the two series resistances R_a and R_1 can be combined into a single resistance of 48.6Ω as shown at Figure 2F.

A simple asymmetrical T-pad has evolved from the combination of the L-pad at Figure 2A with the π-pad at Figure 2B. The resultant T-pad maintains a *bidirectional* impedance match *and* provides the desired 10dB attenuation.

Although there are formulas to use to

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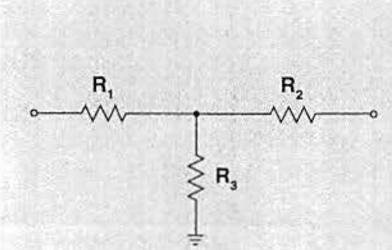


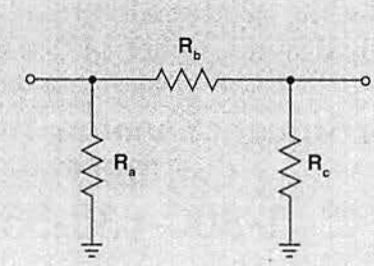
(A)

T to π

$$R_a = \frac{R_1R_2 + R_2R_3 + R_1R_3}{R_2}$$
$$R_b = \frac{R_1R_2 + R_2R_3 + R_1R_3}{R_3}$$
$$R_c = \frac{R_1R_2 + R_2R_3 + R_1R_3}{R_1}$$

π to T

$$R_1 = \frac{R_aR_b}{R_a + R_b + R_c}$$
$$R_2 = \frac{R_bR_c}{R_a + R_b + R_c}$$
$$R_3 = \frac{R_aR_c}{R_a + R_b + R_c}$$



(B)

Figure 1. A T-pad with resistance labeled R_1, R_2 and R_3 is shown at 1A. An equivalent π-pad is shown at 1B. The π-pad resistances are labeled R_a, R_b and R_c. The figure's formulas can be used to convert from a T-pad to an equivalent π-pad and vice versa.

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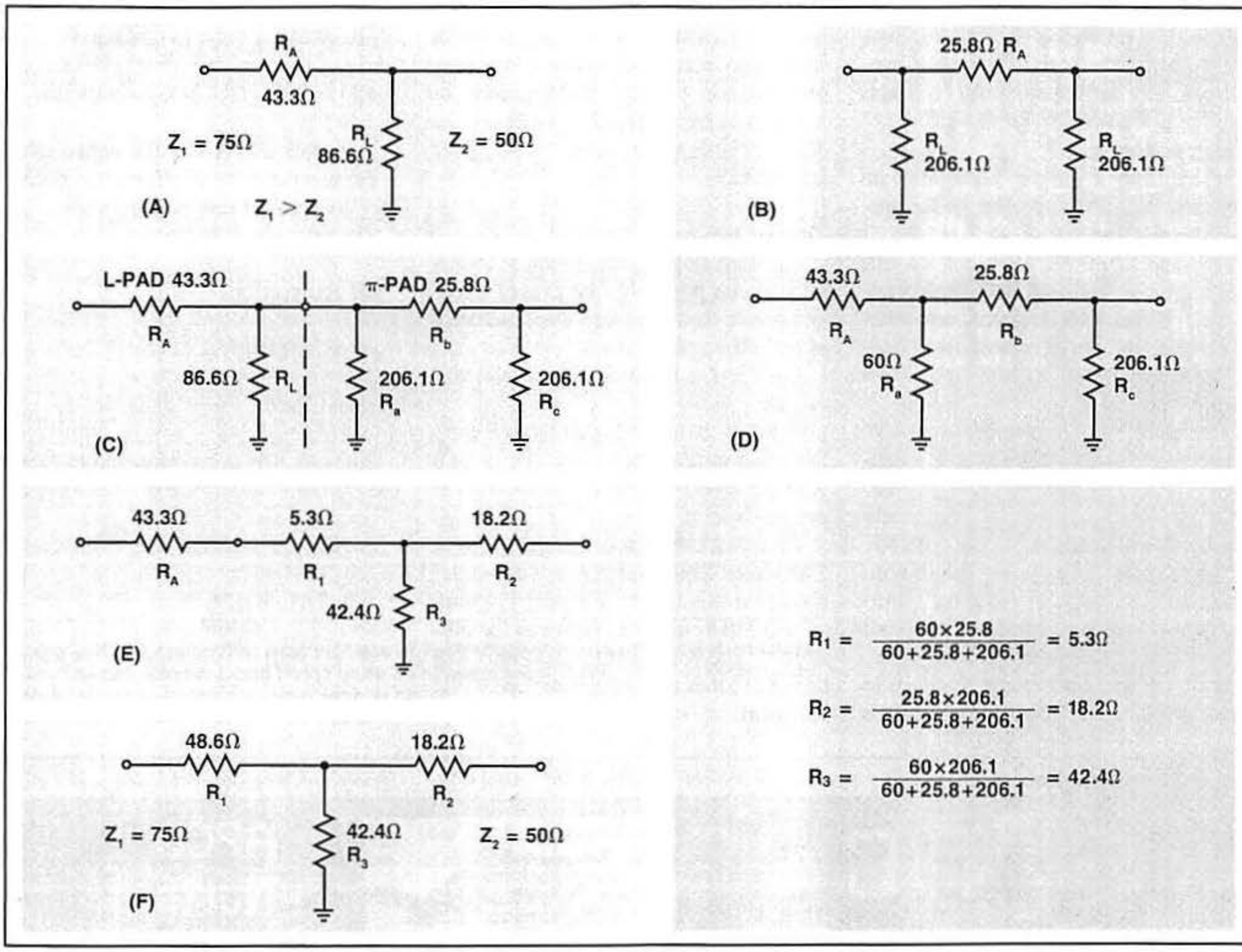

Figure 2. The process of evolution from 2A to 2F can be handled on a simple calculator to design a hybrid pad with 10dB loss.

Express yourself

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design the resultant T-pad at Figure 2F, they are complex and cumbersome to handle. The process of evolution shown in Figure 2 is easier to handle on a simple calculator and actually may be faster.

Construction

In building a simple attenuator or matching pad, it is important to use precision resistors.

Resistors with 1% tolerance should produce an attenuator with sufficient accuracy. Metal film resistors are preferred over composition resistors to provide better operation at high frequencies.

A power rating of $^1/_8$W to $^1/_4$W should be sufficient, unless you accidentally key the transmitter into the pad. Keep lead lengths quite short, especially if you are building a pad to use with RF.

Use a good-quality, shielded construction box, such as the cast aluminum type. The box should be as small as possible.

With asymmetrical pads, be sure to mark or otherwise identify each port's impedance.

When using the various pad formulas, you inevitably will come up with some odd resistance values. You may have to use various combinations of resistors in series-parallel to achieve the desired resistance value. Use your imagination.

Testing the pad

The first step in pad testing is to terminate one port with the proper resistance and then measure the resistance at the other port.

Then repeat the procedure at the other port.

The old, familiar L-pad from Figure 2A appears again in Figure 3B. Here it is being tested with a dc voltage for the proper loss at dc.

This particular pad should show a 5.7dB loss. This does not mean that the *voltage* measured at one port is going to be 5.7dB below the *voltage* at the other port. The voltage at the 50Ω port will be 0.423 times the voltage applied to the 75Ω port.

Using the decibel formula:

$dB = 20\log(E_O/E_I)$, we have:

$dB = 20\log(0.423) = -7.47dB$.

Nonetheless, because the impedances at the two ports are different, it is necessary to apply a correction factor.

The correction factor is:

dB (correction)

$= 10\log(50/75)$

$= -1.76dB$

Subtract this correction figure from the previous calculation of −7.47 to get:

$-7.47 - (-1.76)$

$= -7.47 + 1.76$

$= -5.71dB$

This is the actual attenuation of the

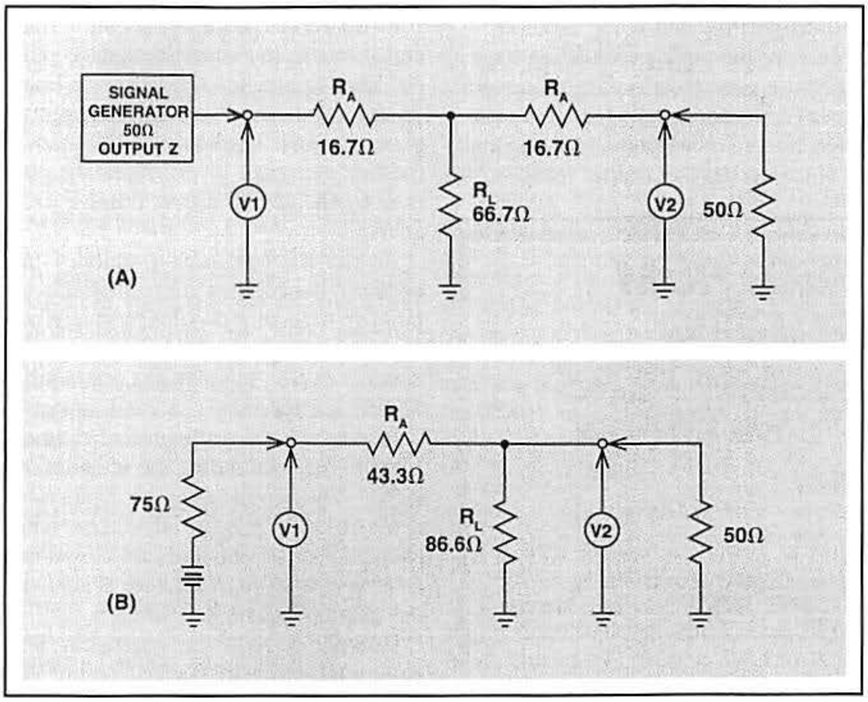

Figure 3. If you are testing a pad for use at RF frequencies, set up the test as shown in 3A. The old, familiar L-pad from Figure 2A appears again in 3B. Here it is being tested with a dc voltage for the proper loss at dc.

L-pad of Figure 3B. The pad's attenuation is bidirectional.

► *Dc loss test*—To perform the dc loss test as illustrated in Figure 3B, you must know the *ratio* of voltage output to voltage input.

For equal input/output impedances, the ratio is found as follows:

$$V_r = \text{antilog}(-\text{dB}/20)$$

For a 6dB pad with equal impedances, the calculation is:

$$V_r = \text{antilog}(-6/20) = 0.501.$$

For the L-pad at Figure 3B, the decibel loss figure is the sum of the pad loss (−5.7) plus the correction factor (−1.76), which equals −7.46dB.

Substituting yields:

$$V_r = \text{antilog}(-7.46/20) = 0.4236$$

In performing the dc voltage test on a pad, be sure that the voltage level you use does not exceed the power-handling capability of the resistors used to construct the pad. Usually a 1.5V battery is a good choice.

As shown in the illustration, a resistance equal to the port impedance is connected in series with the voltage supply. The actual voltage applied across the input port is one-half of the supply voltage.

If the pad passes the ohmmeter and dc voltage checks, it probably is going to be fine to use at least at audio frequencies. If you are testing a pad for use at RF frequencies, set up the test as shown in Figure 3A.

► *RF loss test*—Connect an RF signal generator with a 50Ω output impedance to a 6dB T-pad with 50Ω input and output impedances. Connect a good-quality RF voltmeter first across the input port and record the RF voltage reading. Move the voltmeter to the output port and record the voltage reading.

Attenuation is determined by the formula:

$$\text{dB} = 20\log(E_O/E_I)$$

No correction factor is needed because the voltage readings are taken at the same 50Ω impedance.

If you do not have a sufficiently accurate RF voltmeter, use an RF demod probe in conjunction with a dc voltmeter according to the following method.

Measure the input port's RF voltage. Adjust the generator level to produce a known reference reading on the voltmeter. Record the reference reading and the signal generator output level.

Move the RF probe to the output port and increase the signal generator output level to produce the reference level on the voltmeter. Read the new signal generator level. It should be 6dB above the first generator level. If not, the pad is not suitable for use at this RF frequency.

As the RF operating frequency increases, it becomes more difficult to build an attenuator pad that produces accurate results. Inductive and capacitive effects cause mismatches, and the VSWR increases.

Leakage past the attenuator becomes a problem, invalidating the attenuation rating. The problem can be avoided to some extent by making attenuators with less attenuation per unit and then connecting two or more together to achieve the desired attenuation level.

Leakage around the attenuator becomes more pronounced at higher attenuation levels. At UHF frequencies, such problems quickly become prohibitive. Commercially built, resistive attenuators rated for use to 1GHz and above incorporate special compensating inductors and capacitors along with special resistors to extend the frequency range.

A computer program that aids in the design of all these types of pads, including T-to-π and π-to-T transformations, is available for $5, plus $2 shipping and handling. Write the author at P.O. Box 15178, Spartanburg, SC 29302.